Ultraluminous X-ray Sources and Their Nebulae

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Abstract. One of the interesting features of Ultraluminous X-ray sources is that many of them are surrounded by luminous nebulae exhibiting diverse observational properties. In different cases the nebulae are photoionized or shock-powered. Generally, the two energy sources appear to coexist. ULX bubble nebulae may be considered a new class of shock-powered nebulae similar to upscaled versions of stellar wind bubbles. Their expansion rates support constant energy influx rather than single powerful events like Hypernova explosions.

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INTRODUCTION

We know of Ultraluminous X-ray sources (ULXs) since the late 80th. [1] proposed that some of them could be young SNRs or recent SNe mentioning that other objects require a different explanation. In many cases spectral, spatial and timing properties argue against the SNR explanation, as in the case of NGC6946 X-1 [2].

The object in NGC6946 [3] was not among the first ULXs discovered but probably the first to be identified in the optical range [4]. For several years the object was considered an exceptionally luminous SNR. The second one was HoIX X-1 identified with a complex nebula MH9/10/11 [5]. Today, both remain unique: MF16 as the most compact ULX nebula (ULXN) and MH9/10/11 due to abnormal physical properties and line ratios in the second part of the nebula (MH11, see below).

Direct optical identifications of ULXs are rare and challenge the observational facilities of the largest telescopes. In several cases optical or UV point sources have been detected but probably only in one case [6] has a deep UV spectrum appropriate to determine the spectral class been obtained. The object (NGC5204 X-1) was classified as an early-B supergiant with some peculiarities (see also discussion in [7]).

Optical nebulae are much easier to observe and may provide important information about the central source, acting as calorimeters for the radiation and the mechanical energy source (single explosion or wind/jet activity) connected with the ULX. For distances larger than $\sim 10--20$ Mpc the nebulae become difficult to study as well but the stellar population of the host cluster of star-forming region is usually appropriate for spectroscopy. For distant ULXs it is only possible to study the host stellar population.

ULX NEBULAE

Most of the achievements in studying both ULXs and their optical counterparts were made in the last decade. First in Pakull and Mirioni [8] it was realised that quite a

number of sources may be identified with bubble nebulae. Other ULXs are connected with photoionized nebulae that are usually fainter in Balmer lines but require similar power $\sim 10^{39}$ erg s^{-1}. In general both shock waves and photoionization by the central source contribute.

It was realised that an enhanced He IIλ4686 line is common for many ULXNe [9, 10] including even ULX bubbles [11, 12]. The He II emission is often proposed to be a wind or atmospheric emission of the central object. Pakull et al. [12] probably detected radial velocity variations for the emission line in the optical spectrum of NGC1313 X-2. This result may appear to be the first detection of orbital motion for a ULX. Usually (see [11] and [7]) the He IIλ4686 emission is narrow ($FWHM \lesssim 200$ km s^{-1}) but is emitted in the vicinity of the X-ray source therefore the best explanation is a compact HeIII-region.

Several recent works on ULXNe such as Ramsey et al. [13] cover several objects (up to 8). The number of more-or-less studied ULXNe is slightly higher than this because clear examples are rare. Some of ultraluminous X-ray sources definitely lack a conventional ULXN either because of the different nature of the source or due to environmental reasons (such as rarefied ISM or a crowded star-forming region).

HOST CLUSTERS

In many cases sources are found in young stellar clusters [13, 14, 15] implying that we are dealing with young objects of stellar nature, probably with high-mass X-ray binaries (HMXB). The youngest ages detected are about 4 Myr [13, 15] but it is difficult to judge about the higher age limit due to detectability problems. ULX nebulae residing in large star-forming regions are more difficult to detect. In our work on NGC7331 X-1 [15] that is coincident with a massive young star cluster and HII-region we analyze the low excitation forbidden line excess observed in the spectrum. It may be partially ascribed to the existing interstallar shocks produced by stellar winds and supernova remnants but additional power is required several times higher than the contribution from the several SNRs and wind bubbles predicted by stellar population synthesis. The excess luminosities of the forbidden lines (both of high and low excitation) are quite ordinary for ULX nebulae.

Another example of this kind is the star cluster $n5194-839$ from the catalog of Larsen [16] that coincides within several parsecs with an X-ray source M51 X-7. The cluster was detected by Terashima et al. [17] but not identified with the Larsen object. According to Larsen [16], the cluster is about 12 Myr old. Optical spectrophotometry [11] reveals rather complicated stellar population spectrum with some excess in nebular lines.

KINEMATICS

The kinematics of ULXNe are known much worse than their line ratios and physical conditions (that may usually be traced using diagnostic lines). However it is a potentially important source of information not affected (as line ratios are) by chemical composition. Most expansion velocity estimates were made by order of magnitude. Pakull and Mirioni [8] estimate the expansion rate of the bubble of NGC1313 X-2 as ~ 80 km s^{-1}

having long-slit low-dispersion spectra. [18] obtained echelle spectra of MF16 and detected high-velocity wings at about 200 km s^{-1}. In the recent work by Ramsey et al. [13] echelle-spectroscopy of MH9 is reported. Lines are found to be broadened by ~ 100 km s^{-1}. The importance of kinematical studies of ULXNe is in distinguishing the two energy sources (shock waves and photoionization) that appear to be acting simultaneously in most of the nebulae.

The best way to study more or less quiet kinematics of ULX bubbles is by using scanning Fabry-Pérot Interferometer (FPI) technique. Its advantage against long-slit and echelle spectroscopy is in absence of slit losses and additional information about the three-dimensional properties of the objects. In [19] we analyse our FPI data on MH9/10/11 (associated with HoIX X-1) with ~ 30 km s^{-1} spectral resolution in two forbidden emission lines, [O III]$\lambda 5007$ and [S II]$\lambda 6717$. We show that the expansion of the nebula is anisotropic (velocities spanning the range $30 \div 70$ km s^{-1}) and probably affected by density gradients in the ISM. We also confirm the existence of the second "bubble" in the [O III] line (reported by [20]) coincident with the faint nebula MH11. MH11 differs kinematically from MH9/10: velocity dispersion is $\lesssim 10\,km\,s^{-1}$, and the line-of-sight velocity changes by less than $20\,km\,s^{-1}$ within the nebula. Line ratios differ very much, too: the luminosity of MH11 in [O III]$\lambda 5007$ is about ten times higher than in Hβ. We show that the observed properties of MH11 may be explained by photoionization acting in a rarefied medium with hydrogen density $n_H \sim 0.2 \div 0.3\,\mathrm{cm}^{-3}$.

While we prepared the paper on MH9/10/11 an article by [21] appeared where quite a distant ULX was studied with a scanning FPI. Hence we were not the first to apply this technique to ULXNe. However the authors only detected two velocity components shifted by ~ 60 km s^{-1} with respect to each other. The question is open whether they detected an expanding shell or two overlapping HII-regions with different line-of-sight velocities.

THE NATURE OF ULX BUBBLE NEBULAE

In Figure 1 we show several ULX bubble nebulae with measured expansion velocities. IC10 X-1 was added though it is not a bona fide ULX but a more or less proven Wolf-Rayet HMXB with about-Eddington X-ray luminosity [22]. However the similarity between the bubble in IC10 and ULX bubbles was noted by [22] and appears to hold when kinematical data are considered. Little velocity scatter and dependence on the size indicate that constant energy influx is a more likely solution for ULX bubbles. The solution shown in Figure 1 by dotted lines is taken from [23] and is valid for adiabatic-stage and pressure-driven bubbles:

$$R = 110 n_0^{-1/5} L_{39}^{1/5} t_6^{3/5} \text{ pc} \tag{1}$$

$$V = 64 n_0^{-1/5} L_{39}^{1/5} t_6^{-2/5} \text{ km s}^{-1} \tag{2}$$

Here, n_0 is the hydrogen density of the unshocked material. L_{39} and t_6 are the kinematical luminosity in 10^{39} erg s^{-1} and the bubble age in millions of years. The dependence between V and R is rather shallow in that case, $V \propto R^{-2/3}$ and may be opposed to the solutions for SNRs. $V \propto R^{-3/2}$ for Sedov solution and $V \propto R^{-5/2}$ for the radiative stage

[24]. In the figure we show also the pressure-driven snow-plough solution for a radiative SNR for comparison.

Two well-known hypernova remnant (HNR) candidates in M101, NGC5471B [25] and MF83 [26], fall exactly in the same region of the diagram. Due to that reason they are probable candidates for ULXNe without the ULX phenomenon. In this scope it is also reasonable to consider the bubble in IC10 not a remnant of a powerful explosion [27] but rather a relic ULX bubble. The consistency between the observed properties of shell-like ULXNe may be considered the strongest evidence for the nature of the enigmatic sources. HMXB evolutionary scenarii predict that the ultimate stage of evolution of an HMXB similar to SS433 is a Wolf-Rayet + Black Hole binary similar to IC10 X-1 [28]. The characteristic evolutionary time is of the order of 1 Myr consistent with the observed kinematical ages of the oldest ULX bubbles.

Supercritical accretor models for ULXs [29, 30, 31] favour mild geometrical collimation of the emergent X-ray radiation. Due to that reason the number of ULXNe is expected to be higher than the number of ULXs – off-axis ULXNe are expected to exist. I would suggest to search for off-axis ULXNe among the brightest SNRs having Hα luminosity $\gtrsim 10^{37-38}$ erg s^{-1}.

CONCLUSIONS

Most of the results on ULX nebulae and host clusters are related to a limited number of spectacular sources like HoIX X-1, HoII X-1 and NGC6946 X-1. Deeper studies of the well-known ULXNe reveal similarities among these objects that appeared very diverse at first. For example, photoionized regions of high excitation were discovered near the "classical" bubble ULXN around HoIX X-1 and appear to be created by the same source.

It seems that ULX bubbles are indeed bubbles blown by wind or jets rather than remnants of powerful exposions. In addition to the high mechanical luminosity photoionizing X-ray/EUV radiation of the central source is responsible for some observed features of ULXNe.

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REFERENCES

1. G. Fabbiano, *Annual Reviews on Astronomy and Astrophysics* **27**, 87–138 (1989).
2. T. P. Roberts, and E. J. M. Colbert, *Monthly Notices of Royal Astronomical Society* **341**, L49–L54 (2003), `arXiv:astro-ph/0304024`.
3. E. M. Schlegel, *Astrophysical Journal Letters* **424**, L99–L102 (1994).
4. W. P. Blair, and R. A. Fesen, *Astrophysical Journal Letters* **424**, L103–L106 (1994).
5. B. W. Miller, *Astrophysical Journal Letters* **446**, L75+ (1995).

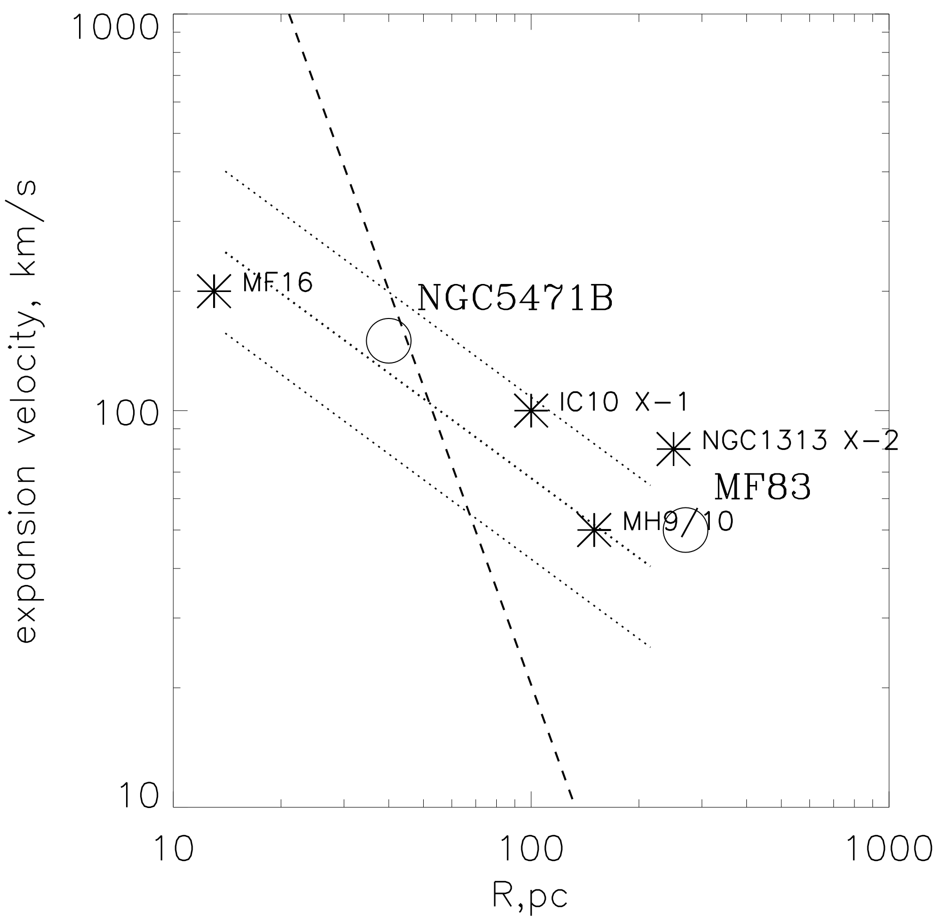

FIGURE 1. Radii and expansion velocities of ULX shells. Three dotted lines correspond to pressure-driven bubble solutions for $L = 10^{39}\,erg\,s^{-1}$ and ISM densities $n = 1$, 10 and $100\,cm^{-3}$. Dashed steep line corresponds to a radiative supernova solution with $E = 10^{52}\,erg$. Two HNR candidates in M101 are shown by circles.

6. J.-F. Liu, J. N. Bregman, and P. Seitzer, *Astrophysical Journal* **602**, 249–256 (2004), `arXiv:astro-ph/0501305`.
7. P. Abolmasov, S. N. Fabrika, O. N. Sholukhova, and T. Kotani, *Publications of Astronomical Society of Japan* (2008), submitted.
8. M. W. Pakull, and L. Mirioni, "Bubble Nebulae around Ultraluminous X-Ray Sources," in *Revista Mexicana de Astronomia y Astrofisica Conference Series*, edited by J. Arthur, and W. J. Henney, 2003, vol. 15 of *Revista Mexicana de Astronomia y Astrofisica Conference Series*, pp. 197–199.
9. P. Kaaret, M. J. Ward, and A. Zezas, *Monthly Notices of Royal Astronomical Society* **351**, L83–L88 (2004), `arXiv:astro-ph/0407031`.
10. K. D. Kuntz, R. A. Gruendl, Y.-H. Chu, C.-H. R. Chen, M. Still, K. Mukai, and R. F. Mushotzky, *Astrophysical Journal Letters* **620**, L31–L34 (2005).
11. P. Abolmasov, S. Fabrika, O. Sholukhova, and V. Afanasiev, *Astrophysical Bulletin* **62**, 36–51 (2007), `arXiv:astro-ph/0612765`.

12. M. W. Pakull, F. Grisé, and C. Motch, "Ultraluminous X-ray Sources: Bubbles and Optical Counterparts," in *Populations of High Energy Sources in Galaxies*, edited by E. J. A. Meurs, and G. Fabbiano, 2006, vol. 230 of *IAU Symposium*, pp. 293–297.
13. C. J. Ramsey, R. M. Williams, R. A. Gruendl, C.-H. R. Chen, Y.-H. Chu, and Q. D. Wang, *Astrophysical Journal* **641**, 241–251 (2006), `arXiv:astro-ph/0511540`.
14. R. Soria, M. Cropper, M. Pakull, R. Mushotzky, and K. Wu, *Monthly Notices of Royal Astronomical Society* **356**, 12–28 (2005), `arXiv:astro-ph/0409568`.
15. P. K. Abolmasov, D. A. Swartz, S. Fabrika, K. K. Ghosh, O. Sholukhova, and A. F. Tennant, *Astrophysical Journal* **668**, 124–129 (2007), `arXiv:0707.2099`.
16. S. S. Larsen, *Monthly Notices of Royal Astronomical Society* **319**, 893–901 (2000), `arXiv:astro-ph/0008191`.
17. Y. Terashima, H. Inoue, and A. S. Wilson, *Astrophysical Journal* **645**, 264–270 (2006), `arXiv:astro-ph/0603528`.
18. B. C. Dunne, R. A. Gruendl, and Y.-H. Chu, *Astronomical Journal* **119**, 1172–1179 (2000), `arXiv:astro-ph/9912003`.
19. P. Abolmasov, and A. V. Moiseev, *ArXiv e-prints* **806** (2008), `0806.4527`.
20. M. W. Pakull, and F. Grisé, *ArXiv e-prints* **803** (2008), `0803.4345`.
21. M. Rosado, K. K. Ghosh, and I. Fuentes-Carrera, *ArXiv e-prints* **803** (2008), `0803.3003`.
22. F. E. Bauer, and W. N. Brandt, *Astrophysical Journal Letters* **601**, L67–L70 (2004), `arXiv:astro-ph/0310039`.
23. J. Castor, R. McCray, and R. Weaver, *Astrophysical Journal Letters* **200**, L107–L110 (1975).
24. T. A. Lozinskaia, *Sverkhnovye zvezdy i zvezdnyi veter : vzaimodeistvie S gazom Galaktiki*, Moskva : "Nauka," Glav. red. fiziko-matematicheskoi lit-ry, 1986., 1986.
25. C.-H. R. Chen, Y.-H. Chu, R. Gruendl, S.-P. Lai, and Q. D. Wang, *Astronomical Journal* **123**, 2462–2472 (2002), `arXiv:astro-ph/0202047`.
26. S.-P. Lai, Y.-H. Chu, C.-H. R. Chen, R. Ciardullo, and E. K. Grebel, *Astrophysical Journal* **547**, 754–764 (2001), `arXiv:astro-ph/0009238`.
27. T. A. Lozinskaya, and A. V. Moiseev, *Monthly Notices of Royal Astronomical Society* **381**, L26–L29 (2007), `arXiv:0708.0626`.
28. A. M. Cherepashchuk, *Space Science Reviews* **74**, 313–324 (1995).
29. J. I. Katz, *Comments on Astrophysics* **11**, 201–211 (1986).
30. A. R. King, M. B. Davies, M. J. Ward, G. Fabbiano, and M. Elvis, *Astrophysical Journal Letters* **552**, L109–L112 (2001), `arXiv:astro-ph/0104333`.
31. J. Poutanen, G. Lipunova, S. Fabrika, A. G. Butkevich, and P. Abolmasov, *Monthly Notices of Royal Astronomical Society* **377**, 1187–1194 (2007), `arXiv:astro-ph/0609274`.